Numerical and Experimental Research on the Near-Field Optical Virtual Probe

TAO HONG, JIA WANG, LIQUN SUN, DACHENG LI

Department of Precision Instruments, State Key Laboratory of Precision Measurement Technology and Instruments, Tsinghua University, Beijing, P. R. China

Summary: A near-field optical virtual probe (NFOVP) is a type of immaterial tip based on the principle of near-field evanescent wave interference. Evanescent wave interference and the aperture type play very significant roles in generating near-field optical virtual probes. Two evanescent waves, propagating in opposite directions, will interfere to generate the confinement field. The central peak of the wave distribution carries the preponderance of energy. An aperture can be used to suppress the sidelobe in the energy distribution while forming the NFOVP. In this paper, the NFOVP is investigated numerically by means of the three-dimensional (3-D) finite-difference time-domain (FDTD) method. Some significant factors in the creation of the NFOVP, such as the shape and size of the aperture, the incident light, and the specimen (nanoparticle), are studied and discussed. The optical field of the evanescent wave interference has been measured by near-field scanning optical microscopy (NSOM), and the preliminary experimental results are shown.

Key words: near-field optics, evanescent wave interference, near-field optical virtual probe, finite-difference time domain

PACS: 61.16.Ch

Introduction

Near-field optics have been developed extensively in the past two decades, with applications in high-resolution optical imaging, spectral detection, and high-density optical data storage. Due to the advantage that it is beyond the classical diffraction limit, near-field scanning optical microscopy (NSOM) is a very powerful technique for expanding investigations on the mesoscopic scale. The nanoperture optical probe and critical separation requirements are two essential factors that determine the performance of NSOM. The resolution and contrast of the image are determined by the aperture size of the optical probe and the precision of separation distances. Although a high resolution can be achieved by NSOM, it also has some drawbacks. These drawbacks include low transmission efficiency of the probe, slow feedback rate due to the rigorous distance control requirement, and the physical fragility of the probe. All of these factors limit the development of probe type near-field optical systems.

Grosjean and Courjon (2001, 2003; Grosjean et al. 2003) first proposed a theoretical immaterial tip concept by light confinement in 2001 (Fig. 1). A confined light distribution is generated due to the evanescent wave interference. In such a virtual probe, the full width at half-maximum (FWHM) confinement distribution peak is independent of the distance z. The concept of a virtual probe can be utilized to increase the transmission efficiency of the probe and relax the critical condition of distance control of other near-field optical systems.

The near-field optical virtual probe (NFOVP) is a type of virtual tip based on the principle of near-field evanescent wave interference and aperture diffraction (Hong et al. 2002). In this paper, the NFOVP is investigated numerically by means of the three-dimensional (3-D) finite-difference time-domain (FDTD) method. Some significant factors in the creation of the NFOVP are studied and discussed. The optical field of the evanescent wave interference was measured by NSOM and the preliminary experimental results are shown.

Characteristics of the Near-Field Optical Virtual Probe

To understand the formation mechanism and characteristics of the NFOVP, a simulation model was created as shown in Figure 2a. Numerical simulations were done by 3-D FDTD. The whole simulation space was divided into $100^3$ equal discrete units, each of which has the volume of $\Delta x \cdot \Delta y \cdot \Delta z$, where $\Delta x$, $\Delta y$, and $\Delta z$ are all 50 nm. The size of each unit is

Address for reprints:
Wang Jia
Associate Professor
Department of Precision Instruments
Tsinghua University
Beijing 100084, P.R. China
e-mail: wj-dpi@mail.tsinghua.edu.cn
about $\lambda/13$, which satisfies the standard simulation precision requirement in the FDTD method of being less than $\lambda/10$ (Karl and Luebbers 1993). The wavelength of the incident light is 650 nm and the polarization direction is along the y axis. The distance, $h$, between the observation plane and the interface is 250 nm. The refractive index of the two media is 2 and 1, respectively. The incident angle is 45°, which generates total internal reflection. A metal film with a round aperture (diameter $D = 1.5 \mu m$) in its center is located on the interface. The metal film is taken as a perfect electric conductor (PEC) with infinite conductivity. The center of the aperture is defined as the origin of the Cartesian coordinates.

The intensity distribution of the NFOVP on the observation plane (XY) is shown in Figure 2b. The distribution is axial, symmetrical along the y axis, and the y component of the distribution is dominant, which is characteristic of the polarization of the incident light. The cross-sectional view along the x axis (Fig. 2c) of the intensity distribution in Figure 2b shows a very sharp central peak that can be employed as a virtual probe, and two sidelobes.

Simulation results of the virtual probe which met the essential conditions of evanescent wave interference and the light confinement by a small aperture are shown below (Fig. 3). The characteristics of the NFOVP, such as transmission efficiency and the beam width and depth, were investigated and will be discussed in detail.

As shown in Figure 3a, the transmission efficiency has an almost linear correlation with the size of aperture. The order of magnitude of the transmission efficiency is $10^{-2}$, which is 10 times higher than the usual nanoaperture probe with comparable resolution used in near-field optical systems. The problem of low throughput power in NSOM can probably be solved by utilizing the NFOVP.

Figure 3b shows that the FWHM is approximately 280 nm and is constant for any value of distance $z < 600$ nm. In the simulation, the dispersion error induced by the unit size setting is ±25 nm, which will not influence the results significantly. The range over which the FWHM remains constant is 100–600 nm, which determines the effective depth of the NFOVP. This characteristic can be utilized to relax the critical separation requirements in conventional near-field systems. The

![Fig. 1 Concept of virtual probe. FWHM = full width at half-maximum.](image)

![Fig. 2 (a) Simulation models by three-dimensional finite-difference time-domain method; (b) intensity distribution on the observation plane of the round aperture diffraction model; (c) cross-sectional view along x axis of distribution on the observation plane.](image)

![Fig. 3 (a) Transmission efficiency versus aperture size; (b) full width at half-maximum (FWHM) of central peak versus distance; (c) intensity of central peak versus distance.](image)
maximum value of the peak intensity is at 250 nm from the interface (Fig. 3c). Subsequently, the peak intensity decreases as the distance increases, but its decrease to 35% of maximum value is not problematic in the effective range (600 nm) of the virtual probe. This amount of peak intensity is acceptable.

Some Variable Factors Affecting the Near-Field Optical Virtual Probe

In this section, some factors affecting the NFOVP, such as the shape and size of the aperture, the incident light, and the specimen (nanoparticle), will be discussed.

Shape and Size of the Aperture

In the model shown in Figure 2a, if a square aperture is employed, the sidelobes in the field distribution are suppressed more efficiently than with the round aperture (Fig. 4), where the side length, D, of the square aperture is 1.5 µm. In addition, the relationship between the FWHM of the central peak and the distance is quite comparable with the values in the case of a round aperture. The optimization of the aperture is important for the sidelobe suppression in the NFOVP.

In the simulation model of Figure 2a, if the size of the aperture is changed, the optical field distribution of the NFOVP will also be changed. Likewise, if the aperture size is changed, the relationship between the FWHM of the central peak and the distance also changes. Figure 5 shows the difference of the FWHM versus distance with different sizes of apertures. The simulation results indicate that the effect of the evanescent wave on the virtual probe is not significant when the diameter of the aperture is < 1 µm, and the FWHM of the central peak increases quickly with increased distance as shown in Figure 5a. The evanescent wave interference effect develops gradually, and the NFOVP is formed when the diameter of the aperture is > 1 µm. The FWHM of the central peak holds constant over a certain range of distance as shown in Figure 5b and c. This indicates that, in order to produce the NFOVP, the size of the aperture must be greater than a certain minimum size. This minimum value is related to the wavelength of the incident light, the incident angle, and the refractive index of the media. Many sidelobes will also appear with further increase of aperture size, which is not desirable in applications of the virtual probe. In conclusion, an appropriate aperture size and shape is critical for successful applications of the NFOVP.

Incident Light

Some parameters are changed in the model shown in Figure 2a: the incident angle is now 76°, the wavelength of the light is 400 nm, and a square aperture with side length of 0.6 µm is employed. The whole simulation space is divided into 100³ equal discrete units, each of which has the volume of ∆x·∆y·∆z, where ∆x, ∆y, and ∆z are all 20 nm. The relationship between FWHM of the central peak (defined as the width of the NFOVP) and distance is shown in Figure 6a. The results demonstrate that the width of the NFOVP (about 120 nm) decreases with the increase of the incident angle and decrease of the light wavelength. The dispersion error induced by this setting of the unit size is about ±10 nm. The range in which the width of the NFOVP is minimal is shortened to approximately 180 nm. This range is several times larger than the near-field separation in conventional near-field optical systems. The width of the NFOVP can be decreased by increasing the incident angle and decreasing the light wavelength at the cost of shortening the depth of the NFOVP.
The effect on the NFOVP is also very significant even though the size of the aperture is very small (0.6 × 0.6 µm). The NFOVP is influenced not only by the size of the aperture but also by the light wavelength and the incident angle.

To examine the intensity distribution, two incident lights are added whose incident plane is perpendicular to the former two incident lights. The wavelength of the light is 400 nm; the incident angle is also 45°. The polarization directions are perpendicular to their incident planes. The intensity distribution on the observation plane, which is 200 nm away from the interface of the media, is shown as Figure 6b. The distribution is symmetrical and the NFOVP becomes a cylindrical optical probe, which is more suitable for practical applications. The results show that the distribution of the NFOVP can be influenced by changing the form of the incident light.

### Interaction with the Nanoparticle

The simulation model as shown in Figure 7a is built to study the interaction between the NFOVP and the nanoparticle. The wavelength of light is 650 nm; the size of the square aperture is 1.5 × 1.5 µm. A nanoparticle is placed beneath the aperture. The distance, a, between the nanoparticles and the aperture is 250 nm. The diameter of the nanoparticle is 300 nm. Two kinds of nanoparticle are used: one is a dielectric particle (refractive index is 2.1), the other is a gold particle. An observation plane is placed 200 nm away from the aperture to investigate the disturbed optical-field distribution of the NFOVP due to the existence of the nanoparticle.

The simulation results indicate that the optical-field distribution of the NFOVP is affected by the existence of the nanoparticle, but the influence is very limited and does not change the overall distribution of the NFOVP. (Fig. 7b, c, and d).

Notice that the FWHM of the central peak is almost identical, but the intensity of the central peak on the observation plane is different in the three cases. As shown in Figure 8, the peak intensity due to the existence of the dielectric particle is smaller than that in case there is no particle. In the case of the gold particle, the peak intensity is larger than that of no particle. It indicates that the optical field of the NFOVP is enhanced by the existence of the metal particle.

### Direct Measurement of the Evanescent Wave Interference Field

The NFOVP is a type of optical probe that is based on evanescent wave interference. Therefore, direct measurement of the evanescent wave interference field is indispensable for the characterization of the NFOVP. As shown in Figure 9, an experimental setup was built to measure the optical field of the evanescent wave interference by the NSOM. The laser beam (wavelength of 532 nm) enters the Dove prism after it is modulated by the chopper and passes through the polarizer. At the top surface of the Dove prism, the incident angle is 73° and total internal reflection occurs. Then, the laser beam exits the Dove prism, is reflected by the mirror, and returns along the original path. Total internal reflection occurs again at the top surface of the Dove prism. The two evanescent waves of opposite orientations interfere with each other. The evanescent field interference pattern localizes on the surface of the prism.

It is now possible to calculate the intensity distribution and the period of the interference fringes using the following equations.

The intensity of the interference fringes:

\[
I = 2A^2e^{-2kz} \sin^2 \theta \left[ 1 + \cos\left( \frac{4\pi n_1 x}{\lambda} \sin \theta \right) \right]
\]

and the period of the interference fringes:

\[
T = \frac{\lambda}{2n_1 \sin \theta},
\]
where $\lambda$ is the wavelength of the light, $\theta_i$ is incident angle of the total internal reflection, $n_1$ and $n_2$ are the refractive indices of the Dove prism and vacuum, respectively, $A$ is the amplitude of the incident wave, 

$$k_1 = n_1 \omega/c = 2\pi n_1 / \lambda,$$

$n = n_2 / n_1$ is the relative refractive index. In our experiment, $\lambda$ is 532 nm, $n_1$ is 1.5, and $\theta_i$ is 73°. Thus, the calculated value of the interference fringe’s period is 185 nm.

The experimental results are shown in Figure 10. The polarization direction of the incident light is in the incident plane and along the direction normal to the two media interface (TM wave). Figure 10b is the cross-sectional view that is perpendicular to the direction of the fringes. The period of the fringes is approximately 180 nm, which agrees with the calculated value. The FWHM of each peak is approximately 100 nm.

It was also possible to examine the intensity of the evanescent wave interference field at different distances from the interface of the two media. The experimental results are shown in Figure 10c. The optical intensity of the interference field decreases quickly as the distance increases, which is a well-known characteristic of evanescent waves. When the distance is approximately 170 nm from the interface of the two media, the optical intensity becomes $1/e$ of the maximum.
Conclusions

The NFOVP is based on evanescent wave interference and a precise aperture shape. It has a transmission efficiency rate 10 times higher than that of the ordinary nanoaperture probe with comparable resolution used in NSOM. The FWHM of the central peak of the virtual probe remains constant over a certain range. The effective distance of the NFOVP is approximately 10 times longer than conventional near-field distances because of its unique characteristics. The distribution of the virtual probe could be influenced by the shape and size of the aperture, the parameters of the incident light, the specimen, and so forth. The interaction between the NFOVP and the nanoparticle was studied. The evanescent wave interference fringes have been measured directly by NSOM and a clear optical image of the fringes was obtained. The experimental results agree with theoretical expectations. These are only preliminary experimental results; further research and experiments will be conducted.

This type of probe is likely to be used in near-field optical data storage, nanolithography, near-field optical imaging and spectral detection, optical manipulation, and so forth.

Acknowledgment

The authors are grateful for research support from the National Research Fund for Fundamental Key Projects No.973 (G1999033002), Chinese National Nature Science Foundation Project No. 60278029, Tsinghua University’s 985 Foundation For Optical Information Storage (a subproject of Near-field Optical Storage).

References